Tianfeng Wan

The Tectonics of China

Data, Maps and Evolution

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With 156 figures, 52 of them in color

高等教育出版社
HIGHER EDUCATION PRESS

Author
Prof. Tianfeng Wan
School of Earth Sciences & Resources
China University of Geosciences (Beijing)
Beijing 100083, China

ISBN 978-7-040-29534-4
Higher Education Press, Beijing

ISBN 978-3-642-11866-1 e-ISBN 978-3-642-11868-5
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2009943830

Cover design: Frido Steinen-Broo, EStudio Calamar, Spain

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

The theory of plate tectonics was introduced to China in the early 1970s. During the last thirty years, both Chinese and foreign geoscientists have undertaken many studies which contributed to our understanding of the tectonics of the Chinese continent, by systematically analysing and summarising considerable amounts of data accumulated by regional geological surveys, and by improvements in the methods of research. These studies concerned not only the distribution and geometry of tectonostratigraphic units and their deformation, but also the kinematics, dynamics and causes of rock deformation and movement of the lithospheric plates. As a result of these studies, many new and surprising phenomena have been discovered, and many new concepts have also been developed. Research has progressed from purely qualitative assessments of the amount of deformation, with the forces and rates of movement involved, to numerical calculations providing more quantitative estimates. Concepts have also evolved from the presumption that the Earth's crust is essentially stable to an appreciation that it is in constant movement. These aspects will be discussed in this book.

Tectonics is now an essential component of studies in Earth Sciences, providing the scientific basis for the discovery and exploitation of new mineral deposits and energy resources, the protection of the environment and the prediction and reduction of the effects of natural hazards. There is an urgent need to summarise systematically the abundant recently acquired tectonic data for scientific research, exploitation of mineral deposits and energy resources and the protection of the environment.

The factual and theoretical basis for studies in tectonics is provided by developments in: (1) Regional geological studies; (2) Tectonic models; (3) Methods of tectonic analysis; (4) Concepts of tectonic evolution.

Regional geological studies provide the foundation for the study of tectonics and have been conducted in China since 1949. Regional geological maps at 1:1,000,000 scale were compiled for the main part of Chinese continental territory in [illegible] 1960s and at 1:200,000 scale from 1960s to 1980s (published as provincial geological maps of China, 1984–[illegible]). Based on these data, tectonic units have been identified, discussed and analysed carefully in each region (Huang JQ (1984, [illegible]), also known as Huang TK, 1945, 1960, 1964, [illegible], 1984, 1987; Group of Regional Geology, Hebei College of Geology, 1979; Ren JS et al., [illegible], 1990, 1996, 2000; Yang and Yang, [illegible]; Cheng YQ, 1994; Che ZC et al., 2002). Local and regional tectonic characteristics are now well understood, but Chinese geoscientists recognized larger scale tectonic features and integrated the regional features into the tectonic development of the Chinese continent comparatively later than the geoscientists abroad as a whole. However, the use of fixed tectonic units does not provide an appropriate basis for the description of the tectonics of China, as during the course of geological evolution the effective tectonic units have changed throughout.

Tectonic models have provided important concepts for understanding tectonics. Li Si[illegible] (1889–[illegible]), also known as Lee J.S. (1926, 1947, [illegible]) proposed a structural system based on a combination of the features of rock deformation and the different types of stress: e.g. "geosilon" type, "S" (or echelon?) type shear structural system, parallel structural system, longitudinal structural system, latitudinal structural system, etc. However, this classification will not be used in the following chapters.

Most recent monographs and textbooks on tectonics (e.g. Condie, 1982, 1997; Kearey and Vine, 1996; Van der Pluijm and Marshak, 1997; Dresker, 2001; Erickson, 2001) used the same theoretic models: (1) convergent tectonics (subduction, collision, indentation and thrust belts); (2) divergent tectonics (ocean ridges, rifts, extensional basins, detachments and metamorphic core complexes); (3) transform tectonics (transform and strike-slip faults); (4) inversion tectonics acting on earlier tectonic systems. This theoretical system emphasizes the mechanisms and the geometry of each tectonic model, and is easy to be understood. However, this system does not place much emphasis on tectonic history. The system emphasizes the tectonic analysis of specific geological situations, but it is important to realize that geology or geosciences is essentially a historical science, and that many changes and many different tectonic events have affected the lithosphere for more than four billion years of Earth history.

It is really important for us to research the methods of tectonic analysis. However, only emphasizing the methods but never discussing the tectonic evolution in detail, as Ma WP (1992) did, has been proved ineffective.

Many monographs and papers emphasize on the historical aspects of the tectonics of China have been published by Huang JQ (1945, 1960, 1974, 1980, 1977, 1984, 1987), Li CY et al. (1980, 1982, 1984), Wang HZ (1982, 1985, 1990, 1994), Ren JS (1980, 1990, 2003) and Zhang and Hou et al. (1986). These studies are concerned with "Historical Tectonics". On one hand, researchers engaged in historical tectonics pay more attention to stratigraphy and the characteristics of geological formations and their origins, and analyse their lithological and paleontological characteristics, their provenance, environments of formation and the origins of the sedimentary and magmatic rocks, with emphasis on their historical evolution. On the other hand, tectonic modelers pay more attention to the transformation of rock bodies, i.e. rock deformation, structural geometry, kinematics and dynamics, with emphasis on the mechanisms of deformation. Although most researchers engaged in tectonics agree that both geological formation and transformation should be studied, and that historical and mechanical analyses should be combined, due to the differences in training, experience and the focus of their interests, these different approaches may produce different results. Zhang WY (1983, 1984) et al. (1986, 1988) advocated that these approaches should be integrated in the study of the tectonics of China. The author considered that it is really important for us to follow these precepts in the present volume, though it is very difficult.

In this book, the author did his utmost to combine the studies of formation and transformation using the plate tectonic theory together with historical and mechanical analyses. Abundant and recently acquired geological, geochemical and geophysical research data are applied to describing and discussing the sequence of tectonic events which have affected the Chinese continental lithosphere from the Archean to the Recent. Until the present time, it is difficult to achieve this aim because of the scarcity of data on some periods and provinces.

In this volume, for understanding the tectonics of China, the author puts forward many new views: calculating the thickness of the continental crust of the Sino-Korean plate during the Archean and Paleoproterozoic; determining the periods during which the Supercontinent of Rodinia broke up and the continental blocks were amalgamated to form the Chinese continent; establishing the stages during the Neoproterozoic in which tillites were deposited on the Sino-Korean and Yangtze plates respectively; following the changes in the latitudinal and longitudinal distribution of the Chinese continental blocks during the Paleozoic. During the Late Paleozoic and Triassic, most of the continental blocks which constitute China collided and were amalgamated with the Eurasian Plate. Subsequently China continent was affected by intraplate deformation, with three periods of shortening in the Jurassic: Yanshanian and Indosinian Period (208–135 Ma); Sichuanian Period (135–56 Ma); Himalayan Period (23–0.78 Ma); two periods of shortening with a north-west-trending: Yunnanian Period (56–23 Ma); North Sinian Period (56–23 Ma). Since 0.78 Ma (Neotectonics Period), the state of stress among the plates which constitute the Chinese continent has been nearly in equilibrium.

In this volume, the characteristics of many collision zones in the Chinese continent are analysed in detail; the variations and discussed in terms of the thickness of the crust and the lithosphere; a new hypothesis is proposed for the thinning of the lithosphere beneath the eastern China continent, which is possibly induced by the [illegible] of the continental crust extending across onto oceanic mantle; the control of the environment by tectonics is recognized; the influence of intraplate extension during the Mesozoic–Cenozoic on periods of hot fluid mineralization in China is made understood, and new hypotheses about the dynamic mechanisms that control global tectonics are evaluated.

This book was originally written by the author in Chinese and published by the Geological Publishing House in Beijing in 2004. After incorporating many useful comments, the book was translated into English, with a reduction of local terms and the removal of quotations which were not necessary to the foreign readers. Throughout, the emphasis has been placed on large scale features and the major tectonic events which have affected the Chinese continent. Some errors in the initial version have been corrected following the suggestions of experts in specified fields. For the sake of the foreign readers, the latitudes and longitudes of critical localities have been inserted. Original data are recorded in Appendices, and a large number of references are cited, particularly from the Chinese literature, to facilitate further research in Chinese tectonics.

Tianfeng Wan
Beijing, October 2010

Acknowledgements

Academician Hongzhen Wang, an academic leader in the field of tectonics of China at China University of Geosciences, has encouraged me to write this book, and his system the example influenced people's conception and recognition of tectonics of China.

The publications and lectures by many leading authors provided information for this book, including Academicians Changwen Yu, Xuchang Xiao, Tingdong Li, Qi Zhang, Guowei Ding, Yusheng Zhai, Hengrei Zhang, Zengqian Hou, Dalai Zheng, Jishun Ren, Guowei Zhang, Guangding Liu, and Jiwen Teng; Professors Peiren Zhuang, Jin Bai, Xinfa Qiao, Zhendong You, Jianpei Lin, Fengxiang Lu, Chongjie Zhao, Xianglin Qian, Guoqi He, Weiran Ma, Xiaolong Xie, Xianghua Meng, Ming Ge, Hanlin Chen, Lei Zhao, Hongwei Ma, Hefa Liu, Weixiang Wang, Dongyu Li, Runjin Zeng, Yadong Zheng, Shunchi Peng, Daiwei Liang, Wentao Yang, Honglin Song, Jiening Qiu, Lifang Ma, Zhengwen Wu, Hong Zhu, Zhihe Ren, Yingguo Zhao, Liming Liu, Chongqi Wang, Yue Zhao, Di Wang, Shaofeng Liu, Zhaohua Luo, and Dr. Yang Wang. I would like to thank Prof. Kent C. Condie (University of New Mexico, USA), Jin Bai, Xinfu Qiao, Xianghua Meng and Dr. Jinhua He for providing figures and original data.

I am also grateful to the following people for their assistance in the parts of initial translation of this book: Dr. Zhengyu Wang for Chapters 2 and 3, Shaoran Zhang for Chapters 4 and 5, Mingming Wang for Chapters 8 and 9, Hanwan Wang for Chapters 10 and 11, Wenan Lin for Chapters 12 and 13, and Chuanming Wei for Chapter 15.

I am especially grateful to Dr. A.J. Barber (University of London, UK), who revised and polished the whole text. Without his kind help I couldn't have completed the manuscript in English.

Prof. M.H.P. Bott, Prof. Guangrong Shi, Prof. B. Windley, Dr. J.R.M. Cocks, and Dr. J.R. Ali made many important comments on and suggestions for this English edition. I would like to thank them all here.

Although the preparation of this book is the responsibility of the author, it really represents the collective literary and scientific creation of many researchers, colleagues and friends. I would like to express my heartfelt gratitude for their invaluable help and guidance.

Contents

Chapter 1
Introduction

Tectonics is a comprehensive subject area involved in Earth Sciences concerning the historical development, evolution and origin of the Earth. The aims of this subject are to determine the composition, the structure, the movement (tectonic deformation and displacement) and the evolution of the outer shell of the solid Earth, the lithosphere, and its relationship to activity in the interior, in the lower mantle and the core. This subject area is encompassed in the Theory of Plate Tectonics originating from the investigation of the ocean floors in the 1960s, and combined with the theory of continental drift, which was until then not universally accepted, evolved into a comprehensive theory of global tectonics. Result

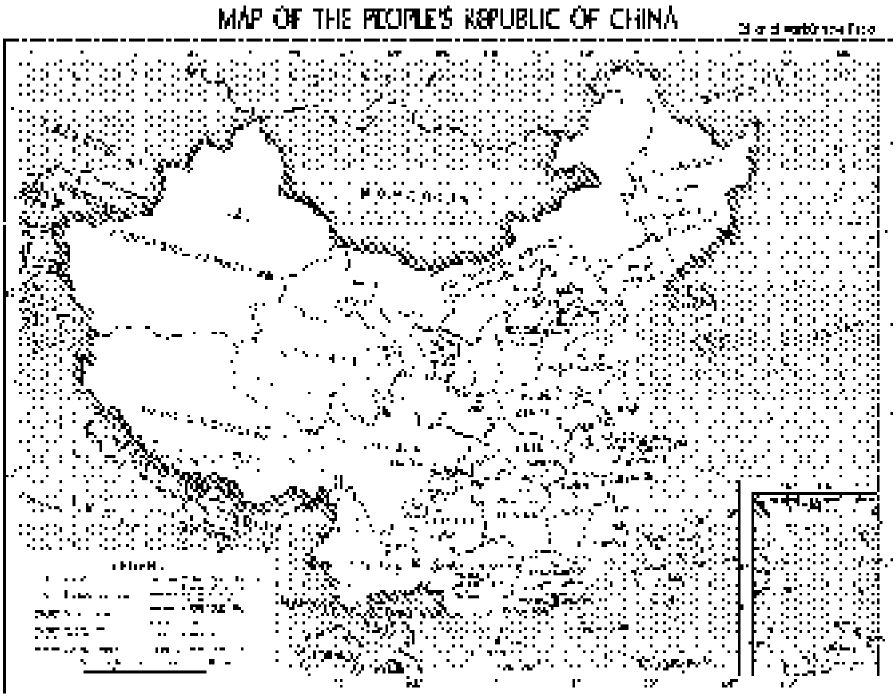

Fig. 1.1 [illegible] China).

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formal branches of the geosciences, geophysics and geochemistry, including isotope geochemistry, petrol-
ogy, stratigraphical paleontology, micropaleontology, paleoclimatology and paleogeography contribute to the

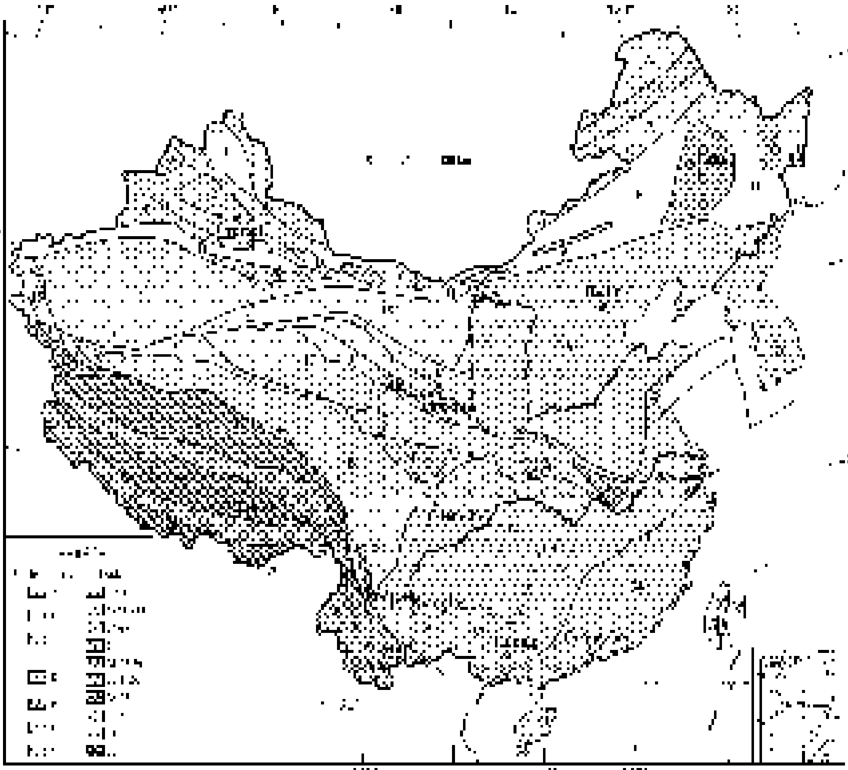


Fig. 1.2 [illegible] of China during the Paleozoic

[illegible]

development of this subject area, encourage the cooperation of specialists engaged in all the geoscience disciplines in the construction of a comprehensive Earth Sciences system.

In this book, the tectonics of China (Figs. 1.1 and 1.2) is dealt with as a sequence of tectonic events through geological time. A comprehensive analysis of these events is based on the integration of records preserved in the rocks, which provides the evidence of the deformation produced by the movement of continental blocks during processes of the subduction, collision and intra-plate compression and extension.

The tectonic systems developed during these events are described in terms of rates of movement, orientation of tectonic stresses, magnitudes of stress, and the timing and rate of deformation. These tectonic and structural aspects are integrated together with the [illegible] sedimentary record, paleo-magnetic data and tectonic reconstructions of the distribution of continental blocks at different geological periods based on paleomagnetism, rock deformation and paleo-biogeographical data. As far as possible all these aspects are dealt with in a quantitative and a purely qualitative manner.

The Chinese continent is located in Eastern Asia (Fig. 1.1), composed of the Qinghai-Xizang (Tibet) Plateau, the Inner Mongolia-Ordos-Yunnan-Guizhou Plateau, the Tarim Basin and Junggar Basin and their surrounding mountains, and the eastern plains and hills. Tectonically, the Chinese continent consists of many continental nuclei and small blocks, which were gradually amalgamated to form the present Chinese continent. Until the Paleozoic, [illegible] tectonic blocks had been identified in the Chinese continent (Fig. 1.2) and classified into five tectonic domains, which will be discussed in detail in later chapters. The evolution of the Chinese continent was very different from the evolution of the North American, South American, Eurasian, African and Australian continental plates.

1.1 Tectonic Events

Concept: Before discussing tectonic events it is necessary to introduce the concept of the tectono-stratigraphic unit (or [illegible]) first proposed by geologists of the Soviet Union in the 1940s and introduced to the study of the tectonics of China by Zhang W.Y. (1959). American geologists have also used a similar concept, the "tectonosequence", more recently (Muehlberger and Travers, 1989).

A tectono-stratigraphic unit encompasses all the tectono-stratigraphic features of a tectonic unit distinguished by a particular type of deformation developed during a particular tectonic period. In terms of time, a tectono-stratigraphic unit represents a period in the tectonic evolution of the Earth. In space it covers the area affected by a specific tectonic event (Fig. 1.2).

The boundary of a tectono-stratigraphic unit is taken at a break in sedimentation, marked by a regional angular unconformity which separates two tectono-stratigraphic units (Fig. 1.3). The tectono-stratigraphic unit lies between two angular regional unconformities. An angular regional unconformity is formed when an older rock unit deformed by either compression or extension is then uplifted, eroded and buried by younger rocks. The boundaries of tectono-stratigraphic units should not be taken at parallel unconformities or disconformities, as these do not represent significant tectonic events.

Different tectono-stratigraphic units are characterized by different types, styles and degrees of rock deformation, with different intensity, resulting from different stress orientations in different tectonic environments (Fig. 1.3). The geological time occupied by a tectono-stratigraphic unit is a "tectonic period". Each tectonic period can be divided into a stable (or "uniform") period, which lasted for a relatively long period of time, and an active (or "catastrophic") period which occupied a much shorter period of time at the end of the tectonic period (Table [illegible]). Each tectonic period commences with a long and stable period and ends with a short and active period. Movement of plates, rock deformation and the related metamorphism and magmatism mainly constitute a tectonic event during the shorter and active tectonic period. By convention, these tectonic events are named after the area in which the tectonism was first recognized. However, if these events are named after their geological or isotopic age, to make

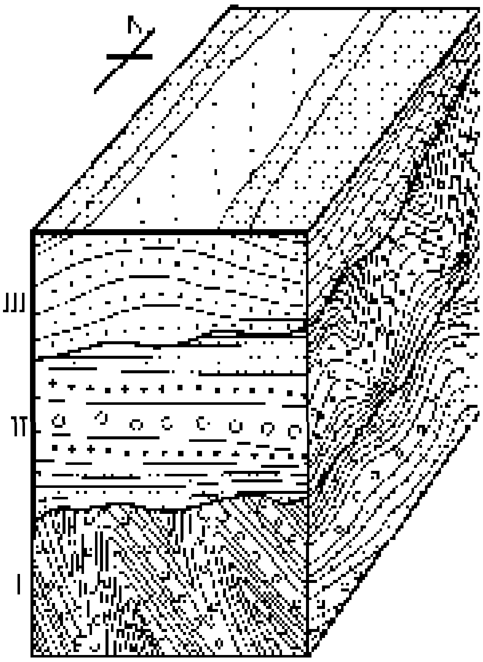


Fig. 1.5 [illegible]

I. [illegible]
II. Transitional [illegible]
III. [illegible]

international comparison becomes easier. Conventional terms, derived from local tectonic periods or local events, are therefore used as little as possible in this book.

The degree and style of tectonism are different in the active and passive periods, but there is usually some connection and inheritance; for example, the orientation of tectonic stresses and the direction of plate movement may be the same in both periods. However, the styles and rates of rock deformation are very different, the magnitudes of the stresses are different and the types of magmatic activity and metamorphism are also very different (Table 1.1).

1.7 Universal Tectonic Events?

Stille ([illegible]) proposed that there was a rhythm in the tectonic evolution of the Earth and that geological history was punctuated periodically by orogenic phases, which occurred at the same time in different parts of the world. In the 20th century this principle exerted a great influence on the development of tectonics, but has generated continual controversy since it was first put forward. In contrast, Soviet structural geologists ([illegible]) considered that rock deformation occurred continuously, with changes taking place over long periods of geological time (e.g. Vostokov [illegible], 1964), and some American geologists (e.g. Gilluly, 1949) not only disagreed with the concept of phases of universal orogeny, but

Table 1.1 Static and active periods in Earth's evolution

Type	Static or uniform behaviour	Active or episodic period
Period of time	~10^8 years	~10^7–10^6 years
Atmosphere	Static average of climatic zones and air temperature	Great change of climatic zones and temperature
Hydrosphere	Static sea level, water quality and water temperature	Great change of sea level, water quality and water temperature
Biosphere	Static propagation and reproduction	Mass extinction
Palaeomagnetism	Static paleomagnetic orientation	Polarity reversal
Sedimentation and erosion	Continuous sedimentation, weak erosion	Partial sedimentation, tectonic activity, strong erosion
Strata boundary	Conformity or partial geographic unconformity	Regional angular unconformity
Geothermal	Static accumulation, weak geothermal action	Great geothermal release and volcanism
Magmatism	Minor magmatic activity, minor intrusion	Widespread magmatic activity
Metamorphism	Local contact metamorphism, weak metamorphic effects	Regional and dynamic metamorphism, widespread thermal effects
Tectonic stress	Gradual accumulation of stress, and release of stress	Stress release and adjustment of stress
Vertical motion of plates	Static depression and uplift	Strong depression and uplift
Horizontal motion of plates	Weak movement	Strong activity
Brittle deformation	Slight deformation, weak small fractures	Strong, various types of fold and fault developed
Astronomy	Solar system distant from galactic disk	Solar system just passing through galactic disk
Meteorite impact	Small and weak impacts	Major impacts

supposed that tectonism had occurred continuously throughout the whole evolution of the Earth (Wang HZ, 1996). In the 1970s–1980s, based on the recognition that sea-floor spreading was a continuous process, the opinion that synsedimentary structures had developed over long periods of time, and the scarcity of unconformities in thrust zones or within orogenic belts, fewer geologists were willing to accept Stille's (1924) proposition. At present, the consensus view is that the Earth is a rheomorphic solid, and is able to flow continuously under differential pressure, so that tectonism and orogeny have occurred uniformly throughout geological time and that there has been no periodicity or rhythm during the tectonic evolution of the Earth (e.g. [illegible], 1981; Sengör, 1982; Hsü, 1989; Li JL, 199[illegible]; Zhang ZC, 1996).

Wang HZ (1982, 1985, 1998) advocated the concept of "rhythmicity" for the tectonic evolution of China, in which deformation has occurred during episodes of tectonic activity periodically in different areas and at different times. From a comprehensive assessment of a large volume of tectonic data, Wang HZ (1997) concluded that there is no evidence that important tectonic events occurred at the same time in different parts of the Earth. However, it is evident that tectonism has occurred over very large areas at approximately the same time in subduction zones, in collision zones and in areas of intraplate deformation. For example, Caledonian tectonic events occurred at almost the same time (420–425 Ma) in a zone extending all the way from the Appalachian Mountains in eastern America to Scotland and the western margin of the Scandinavia (Rogers and Dunning, 1991; Kelly et al., 1985; Trench, 2002). Similar extensive tectonic events have occurred in China, which will be detailed in the following chapters.

According to Hsü (1989) and Sengör (1982), if the Earth is a rheomorphic solid, periodicity would not appear in tectonic evolution on the scale of the Earth. According to the concept of uniformitarianism, orogeny is a continuous and uniform process. When the plate tectonic theory was first proposed and data on sea floor spreading was limited, this opinion seemed to be sustained. The original map showing the pattern of magnetic anomalies on the floors of the oceans implied that sea floor spreading was a continuous process, in which the floors of the oceans expanded continuously in the same direction, only varying slightly in the velocity and direction of movement with time (Wilson, 1965; Le Pichon et al., 1973; Press and Siever, 1974). Given the relationship between the expansion of the oceans and mid-ocean ridges and their destruction in subduction zones along the margins of the oceans, it could easily be assumed that the processes of subduction and collision were also continuous processes. However, Hsü (1989) and Sengör's (1992) hypotheses contradicted many discovered tectonic facts before 1990s. When the much more detailed third edition of the magnetic anomaly map was published at the end of the 1980s (Cande et al., 1989; Cande and Kent, 1992; Müller et al., 1996), analysis showed that since the Middle Jurassic (160 Ma) the Pacific, Atlantic and Indian Oceans had all expanded during the same six periods, with movements in different directions and at different velocities (Table 1.2; Fig. 1.4). Sea-floor spreading at velocities of several cm/yr shows that the Earth has the properties of a rheological solid, while the process shows some periodicity. It seems that both phenomena are to some extent connected with general continuity and a superimposed element of periodicity.

Evidence compiled in this volume shows that the tectonic evolution of the Earth has not been linear, with a uniform rate of change, but non-linear, with periodic variations in the rate of change. From our present evidence it appears that the processes continue over a period of time at a more or less constant rate, but are then interrupted by sudden and catastrophic changes. Such qualitative and quantitative changes are characteristic of all evolutionary processes. As Yin (2003) has explained, tectonism, like all other geological processes, should be considered in terms of non-linear dynamics in an unstable system. The evolution of the Earth system should be studied using the complexity ("Chaos") theory.

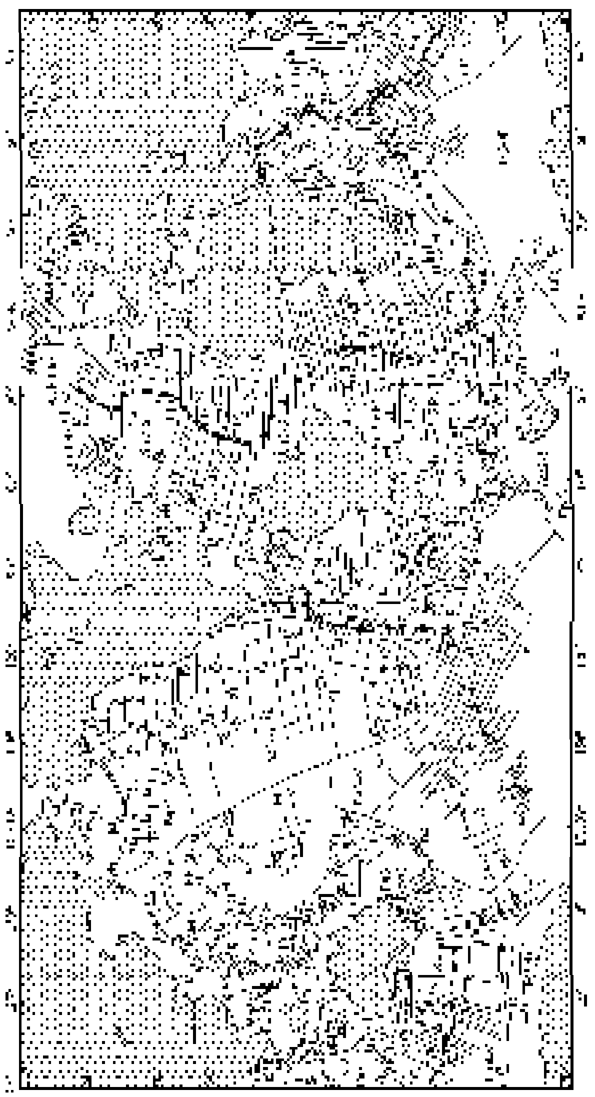
In the past two hundred years, there has been a lively geological debate between proponents of uniformitarianism, who argue that geological processes have continued in much the same way and at the same rate throughout geological time (Hutton, 1795; Lyell, 1830–1833) and proponents of catastrophism who believe that geological processes proceed by infrequent but catastrophic events (Cuvier et al., 1812). At present, most Earth scientists agree that these concepts can be reconciled. It is recognized that there are stable periods (or periods of uniformity) lasting over a long time span, which alternate with active (or catastrophic) periods, occupying a much shorter time span (Hsü et al., 1990). Tectonic events represent this catastrophic period (Table 1.1).

Tectonic events are difficult to resolve, as their complete history is rarely preserved in the geological record. The evidence is never complete. Strong deformation, block displacement, violent magmatism and large-scale uplift of the Earth's surface have resulted in widespread erosion, forming unconformities where the geological record has been destroyed. For this reason the study of tectonics did not advance very rapidly in many parts of the world. In many areas, facts are few, tectonic and geodynamic data are scarce, the geological literature demonstrates that these deficiencies do not deter geologists from engaging in much speculation and guesswork.

Table 1.2 Periods in the evolution of the ocean floor in the Pacific, Atlantic and Indian Oceans

0 Ma	6 stage
10 Ma	5 stage
37 Ma	
54 Ma	4 stage
	3 stage
97 Ma	2 stage
130 Ma	
160 Ma	1 stage

After Cande and Kent (1995); Müller et al. (1996)



1.3 Determination of Tectonic Events in the Chinese Continent

Geological data from whole China, recorded in the Bureau of Geology and Mineral Resources of the Provinces (1984–1996), the *Introduction to Regional Geology of China* (Cheng Yuqi et al., 1994) and the earlier researches of the author (1994), are referred to the international stratigraphic chart (Remane et al., 2000; International Commission on Stratigraphy, 2004) and compiled as a table of the tectonic periods and tectonic events in China (Table 1.2).

The former practice of referring the tectonic periods in China to worldwide tectonic periods is incorrect. A division into tectonic periods and events has been devised purely for the Chinese continent

Table 1.3 [illegible]

Age boundary Ma / Symbol	Geological age	Duration of movement (Ma)	Tectonic periods and events
[illegible]	Middle Pleistocene–Holocene	since [illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Eocene–Oligocene	[illegible]	[illegible]
[illegible]	Middle stage of Early Cretaceous–Paleocene	[illegible]	[illegible]
[illegible]	Jurassic–Early stage of Early Cretaceous	[illegible]	[illegible]
[illegible]	Late Permian–Late Triassic	[illegible]	[illegible]
[illegible]	Middle Devonian–Middle Permian	[illegible]	[illegible]
[illegible]	Middle Cambrian–Early Devonian	[illegible]	[illegible]
[illegible]	Nanhuan–Early Cambrian	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	1000–[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Neoarchean	[illegible]	[illegible]
[illegible]	Mesoarchean	[illegible]	[illegible]
[illegible]	Paleoarchean	[illegible]	[illegible]
[illegible]	Eoarchean		

and these have been given local names (Table 1.3). However, in order to simplify the terms, and for ease of international comparison, the periods and events in this book are named directly after the geological or isotopic ages and local names for tectonic periods or events are used as little as possible.

As shown in Table 1.3, seventeen tectonic periods and events are identified. The extent of our knowledge concerning these tectonic periods and events is very variable. In general, much less is known about earlier periods compared with the more recent ones. Tectonic periods and events in the Archean and Proterozoic are known only broadly, and periods and events in the Paleozoic can only be discussed generally, and although a series of events can be recognized, the geological data is not very detailed and only two periods can be distinguished. The eight tectonic periods and events since the Paleozoic have been researched in much more detail, and as geological data is more abundant and more accurately known, one chapter is devoted to each of these periods.

In the Archean and Proterozoic, in the absence of detailed biostratigraphic divisions, geological stages are defined in terms of tectonic-magmatism, and the divisions are based on the tectono-magmatic evolution of the continental crust. In the periods since the Proterozoic, geological and isotopic ages of the commencement and close of each tectonic period do not coincide with the beginning and end of eras and periods based on biostratigraphy, and the time spans occupied by each tectonic event may be very different (Table 1.3). This is because the climax and end of tectonic periods in China did not occur at the same time as the extinction events indicated by the biostratigraphy; the climax of a tectonic period is always later than the main orogenesis and extrusions.

For example, according to isotopic data from syntectonic magmatism in most areas of China, as shown in Table 1.3, 135 Ma is the most suitable age for the boundary between the Yanshanian and Sichuanian tectonic periods. In the international stratigraphic chart (Remane et al., 2000; International Commission on Stratigraphy, 2004), there are different opinions on the age of the boundary between the Jurassic and Cretaceous, ranging from 135 Ma to 145.5 Ma. From recent studies, most Chinese researchers recognize the boundary between Jurassic and Cretaceous at either 137 Ma or 140 Ma (Li PX et al., 2004). For the age of the boundary between Jurassic and Cretaceous, the author agrees with the opinion of Li PX et al. (2004), that is, the boundary between the Yanshanian and Sichuanian tectonic periods lies between early and middle epochs of Early Cretaceous. Wan TF (1994) originally chose 135 Ma as the age of the boundary between the Jurassic and Cretaceous, but this decision is now reconsidered.

1.4 Research Principles and Methods for Interpreting Tectonic Events

1.4.1 The Rock Record

The study of tectonic events in the active and stable periods of tectonic evolution requires different research methods. Evidence for the active period of tectonic events is commonly preserved in the rocks as structural features such as folds, faults, thrusts, joints, foliations and lineations, which may be accompanied by recrystallization in a process of metamorphism. The internal changes in a rock body or in a hand specimen can be expressed in terms of the amount of deformation or strain it has undergone, i.e. reduction or expansion in volume, shortening or extension. Strain can be determined with respect to changes in the length of three mutually perpendicular principal axes of strain (ε_1, maximum compression = shortest strain axis; ε_2, intermediate; ε_3, minimum compression = the longest extension strain axis), ε_2 may be equal to or have any value intermediate between ε_1 and ε_3. Strain can be measured if the rock contains "strain markers", objects whose original size, shape, distribution and orientation are known and can be compared with their present size or shape (Ramsay and Huber, 1983).

Tectonic events may also be recorded indirectly by syn-tectonic sedimentation. Tectonic events are commonly accompanied by uplift with accelerated erosion, so that the sedimentary record is destroyed. However, the products of erosion may be deposited in marginal depressions or basins around highly deformed areas as molasse or flysch (turbidite) formations, providing a record of episodes of uplift and erosion. Tectonic events may also be accompanied by the intrusion of magmatic rocks with syn-tectonic mineralization and metallic/hydrothermal metamorphism.

The study of sedimentary strata can be used to solve many problems in tectonics, using the sedimentary facies and the sequence of formations in stable periods, for the recognition of unconformities and of episodes of strong deformation in the active tectonic period. These studies are part of a complete study of tectonics.

Methods used in the analysis of sedimentation and palaeogeography are more appropriate to the stable period of a tectonic-stratigraphic unit. A stable tectonic period is represented by the deposition of a continuous sequence of sedimentary strata in a sedimentary basin. During the stable period, variations in the thickness and rates of deposition of sedimentary strata, and changes in the rate of vertical motion of the Earth's crust, with depression or uplift, can be recognized. By determining the sequence of strata and the facies of each sedimentary unit, it is possible to place these periods of uplift and depression in a chronological sequence of events. The statistical methods of measuring the thickness of sedimentary strata and determining rates of deposition since the Mesoproterozoic, as shown in Appendix 2, are very approximate. There is no method of measuring the effects of intermittent depression and uplift although great thicknesses of sedimentary strata are most likely to be the results of multiple phases of depression, sedimentation and uplift, erosion. Also no allowances have been made for the effects of compaction and diagenesis, or for the movement of thrust nappe sheets caused by later tectonic events. The study of syn-sedimentary faults is helpful to determine the history of development of sedimentary basins during a stable tectonic period. A complete calculation, taking account of all these factors, requires an enormous amount of systematic field and laboratory study.

Although a cover of sedimentary rocks, amounting to several tens of thousands of meters, extends over the major part of the Chinese continent, the greater part of the sediment originally deposited on the continent has been eroded away and is no longer preserved. According to statistical calculations by Ronov et al. (1984, after Qiu and Xu 1986), based on the thickness and extent of sediments and their geological age, at present clastic sediments are being deposited throughout the world at a rate of 50–100 [illegible] per year. Most Mesozoic–Cenozoic sediments have been preserved on the Earth surface, of which ~40% is from the Paleozoic, ~20%–10% from the Proterozoic, and less than 10% from the Archean.

The accumulation of paleobiogeographical data and especially the recognition of ecosystems are important for distinguishing different paleoplates and smaller crustal blocks. The reconstruction of paleobiogeographies demonstrates the continual movement of blocks through time and supports the mobilistic concept of tectonics.

1.4.2 *The Geometry of Rock Deformation*

The foundation of the study of tectonics is the determination of the distribution and mutual relationships of rock units as seen in the field, together with their internal structural features such as folds, faults, lineations and foliations. Tectonics involves rock deformation on all scales from the megascopic to the microscopic, from the lithospheric plate to the individual mineral crystal and its crystal lattice; this information can then be integrated into a comprehensive tectonic system (Fig. 1.3). Tectonics is also concerned with the intrusion and extrusion of magmatic rocks and the metamorphism and the recrystallization of rock bodies with the formation of new minerals and new textures, and the relationship of these events to phases of deformation. These relationships must mainly be established in the field by detailed geological mapping and regional geological surveys, complemented by drilling and by deep structural studies using geophysical methods and by the study of rocks under the optical and electron microscopes.

The deformation and the displacement of the lithosphere are the main concerns of the study of tectonics. Although comprehensive methods should be used in the study of tectonics, and research should encompass all branches of the geosciences, the study of rock deformation should be made on the major preoccupation of tectonics, which has been neglected in some recent studies.

Contributions to the knowledge and understanding of rock deformation in China during the last fifty years have been immense. This can be attributed to the extent and success of regional geological surveys. The plan for an all-line geological survey covering the whole Chinese continent, totaling about 9.6 million square kilometers at the scale of 1 : 1,000,000, commenced, but was not completed before 1949. A reconnaissance survey of regional pre-Cenozoic geology at the scale of 1 : 200,000 was completed in the 1960s (unpublished report); a regional geological survey at the scale of 1 : 200,000 was completed for most areas of China before the end of the 1980s (Bureau of Geology and Mineral Resources of Provinces, 1984–1991); a new regional geological survey at the scale of 1 : 250,000 (more than 100 sheets) has been completed recently over whole Qinghai–Xizang (Tibet) plateau; the results will be published shortly. These surveys raised the extent and precision of geological information substantially. Classification and comparison of regional strata, with the description of types, styles, attitudes and the distribution of folds and faults at the macro- and meso-scale, and of magmatism and metamorphism build up the foundation for studying the tectonics of China in this book.

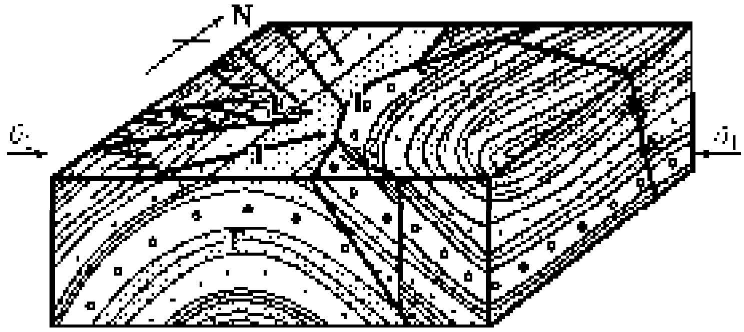


Fig. 1.5 [illegible]

[illegible]

Data concerning the geometry and attitudes of 11,725 macro and meso scale folds (Fig. 1.6; Appendix 1) have been collected and analyzed to determine regional tectonic stress orientations. In the area to the west of 105° where detailed geological surveys at the scale of 1:200,000 have not yet been completed and folds are not shown in considerable detail, geological surveys at scales of 1:500,000 or 1:1,000,000 have been used and the statistics relate to anticlinoria and synclinoria. From these data, it can be seen that rock deformation is widespread throughout the Chinese continental lithosphere. Joint systems, the weakest type of rock deformation, can be found even in the youngest rocks throughout China; it is difficult to find an area not affected by rock deformation.

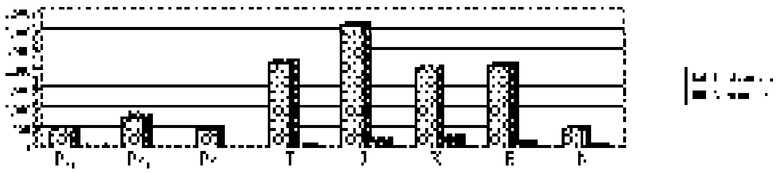


Fig. 1.6 [illegible]

In collision zones, rock deformation is mainly linear with Alpine type folds and [illegible] with high and intermediate angles of dip for the limbs, associated with many thrusts. In intraplate areas covering half the area of China, there is widespread deformation with intermediate strength, in which the angles of dip of limbs are mainly less than 30°, and the folds are accompanied by faults. These two types of deformation are transition zones, belonging to the sedimentary cover detachment type, and may be called Jura type folding. Even in stable tectonic areas covering one third of China which appear to have only horizontal sedimentary strata, there are German type folds with limbs with very low angles of dip and normal faults with high angles of dip and complex joint systems.

1.4.3 The Kinematics of Rocks

The aim of tectonic studies is to examine rock deformation quantitatively, with the determination of the amounts of dilation (changes in volume), distortion (changes in shape) and translation (movements of the rock body as a whole) and the orientation of the stresses responsible for this deformation (Fig. [illegible]), together with the determination of the rates of deformation, rates of shortening, extension and/or horizontal and vertical displacements. It may be necessary to manifest the effects of multiple phases of deformation, where the orientation of the stresses may have been different in each phase. This is relatively easy if the orientation of the stresses in each tectonic period was very different, but may be difficult or even impossible if these stresses were in the same, or nearly the same direction.

Research into the kinematics of the lithosphere aims at determining vertical movements of uplift and depression and horizontal movements of compression, extension and strike-slip movement, and the times at which these movements occurred.

More attention has been concentrated on vertical movements of the lithosphere with the uplift and depression of Earth surface. The determination of vertical movements during a stable tectonic period makes use of data on variations in sediment thickness, changes in lithology and facies; information may also contribute to vertical movements. Vertical movements can be determined through the study of sedimentation and erosion, transgression and regression, the uprise of magma or changes in the thickness of the lithosphere over long periods of time. During the last one hundred years, while these methods were being perfected, it seemed that vertical movements were the most important feature of the kinematics of the lithosphere.

This hypothesis laid the theoretical foundation for concepts of global expansion, limited global expansion, pulsation, etc. More recently, hypotheses of opening and closing (Yang WR et al., 1994, 1996; Jiang CF, 1994, 1996), uplift of the Mohorovičić discontinuity (Chen [illegible] et al., 1992), uplift due to mantle plumes and lithosphere detachment or underplating (Deng JF et al., 1992, 1996, 1997, 1998), which have their bases in this earlier tectonic thought, have exerted important influences over the development of tectonics in China. In these concepts, the tectonic evolution of continents takes place essentially in situ, with vertical movements being the driving force for deformation and displacement, horizontal movements being secondary and limited in their extent. In these hypotheses, the importance of vertical movements has been more fully emphasized, without account for the possibility of great horizontal displacements over distances of several thousand kilometers. In these models, no explanation is offered at all for such great horizontal displacements.

The importance of horizontal deformation and displacement was much more difficult to realize, and it took a long time to be accepted. In 1912, Wegener (1924, republished in 1966) first proposed the Theory of Continental Drift, based on the distribution of fossils and indications of paleoclimatic zones. However, due to unexplained problems and some errors (e.g., it is impossible for the lighter sialic continents to drift at velocities of several meters per year through the denser simatic ocean crust), after detailed discussion at the International Geological Congress in 1922, the theory of continental drift was rejected. However, Wegener's hypothesis was fundamentally correct and formed one of the foundations for the development of the theory of plate tectonics in the 1960s. This example demonstrates the difficulty of changing entrenched scientific thought.

Methods for determining vertical and horizontal movements of the lithospheric plates are summarized in Table [illegible].

The boundaries of the lithospheric plates differ according to the movements of the plates: high-angle normal and reverse faults indicate vertical movements; intermediate and low angle thrusts or overthrusts are characteristics of subduction or collision boundary zones and indicate horizontal thrusts; steep-angle wrench (strike-slip) faults or transform faults indicate horizontal shearing of the plates; intermediate and low angle detachments and listric growth, or syn-sedimentary faults are characteristic of continental rift zones and oceanic ridges and indicate horizontal extension of the plate.

Table 1.4 Research methods for determining movement of the lithospheric plates

Vertical movement	Horizontal movement
	Palaeomagnetism (drift of magnetic poles and changes in palaeogeographic positions) Horizontal changes in palaeobiogeographic characteristics and other palaeoclimatic anomalies
Changes in sedimentary thickness	
Transgression and regression, changes in sedimentary facies	Horizontal migration of sedimentary facies and formations
Horizontal shape changes of plates and continents	Horizontal migration of volcano-plutonic activities, accretionary [illegible]
Magmatism and basin development due to uplift and subsidence of the crust	Horizontal drift of the magmatic center
Progressive and retrogressive metamorphism (P-T-t path)	Horizontal drift of metamorphic facies and zones
Formation of folds	Folding belts
High-angle faulting	Thrust, strike-slip faulting and subduction plate boundaries
Height difference of topography on the surface, valleys, terraces and building on the Earth's surface	Horizontal dislocation of landforms

Ramsay (1967), Ramsay and Huber (1983) proposed a series of methods for determining the strain involved in folding and thrusting, and made significant progress in this field. But parameters and methods for determining vertical strain fields have not yet been developed, and it is difficult to determine rates of compression and extension using conventional methods of structural geology.

Sugisaki (1976) first suggested that there was a relationship between velocities of plate movement and the chemical content K_2O (Wt%), Na_2O (Wt%) and alkali index (A) = [illegible] of volcanic rocks near the subduction zone. In the formula above, the unit of [illegible] is the percentage of weight, the units of [illegible] are the percentage of molecules (Fig. 1.[illegible]). Using these parameters, Sugisaki (1976) discovered that the alkali index increases with more rapid rates of shortening, while Na_2O and K_2O decrease (Fig. 1.[illegible]).

This relationship is not linear, but has an exponential function. These relationships are due to the relative ionic radii of silica and potassium and sodium. The ionic radius of silica is very small, while the ionic radii of potassium and sodium are relatively large. When the velocity of plate movement increases and tectonic activity is enhanced, silica ions are enriched, while the ions of potassium and sodium decrease relatively (Sun Y. 1982, 1995). On the assumption that the velocities of movement involved in marginal and intra-plate deformation are similar, the author (Wan TF 1994) has used the relationships derived from the study of plate margins to quantify intraplate movements. In general, velocities of movement during intra-plate deformation should be less than the rates for marginal deformation. When the velocities of plate movement for the whole Chinese continent are discussed, on the basis of velocities calculated from plate margins, these velocities may be slightly exaggerated. However, all the data have been treated by the same method, so that the relative magnitudes of movement velocities for different areas are comparable.

Sugisaki (1976) used only the relationship between the chemical content of volcanic rocks and velocity of plate movement. The author has used not only the chemical composition of volcanic rocks, but also that of intrusive rocks to estimate the velocities of plate movement. While volcanic and intrusive rocks were formed at the same time in the same tectonic period, the content of major elements in intrusive rocks, especially SiO_2, Na_2O, K_2O, Al_2O_3, is not likely to differ greatly from that of associated volcanic rocks. Wan TF (1994) has made such comparisons many times and found that estimated values of plate movement velocity are almost the same no matter using volcanic or intrusive rocks. Chi [illegible] et al. ([illegible]), Chi [illegible] and Lu [illegible] et al. ([illegible]), Mo [illegible] ([illegible]) and Mo [illegible] et al. ([illegible]) used Sugisaki's method to estimate velocities of extension and compression of blocks in the Cenozoic volcanic areas of eastern China and of the Late Palaeozoic volcanics in the Hengduanshan area. Using this method the